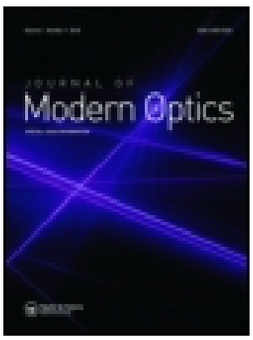

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Design of photonic crystal-based all-optical AND gate using T-shaped waveguide

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ABSTRACT

We present a new configuration of all-optical AND gate based on two-dimensional photonic crystal composed of Si rods in air. Two AND gate structures with and without probe input are proposed. The proposed structures are designed with T-shaped waveguide without using nonlinear materials and optical amplifiers. The performance of the proposed AND gate structures is analyzed and simulated by plane-wave expansion and finite difference time domain methods. The AND gate without probe input needs only one T-shaped waveguide, whereas the AND gate with probe input needs two T-shaped waveguides. The former AND gate offers a bit rate of 6.26 Tbps with a contrast ratio of 5.74 dB, whereas the latter AND gate offers a bit rate of 3.58 Tbps whose contrast ratio is 9.66 dB. It can be expected that these small size T-shaped structures are suitable for large-scale integration and can potentially be used in on-chip photonic integrated circuits.

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All-optical logic gates; T-shaped waveguide; photonic crystal; interference

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1. Introduction

Logic gates are the basic building blocks of digital systems and computing modules. These logic gates are basically used to perform various functions at the nodes of the network such as pattern recognition, pattern matching, data encoding and decoding, and also various switching operations [1]. With the development of telecommunication systems for high data transfer speed and capacity, there is a lot of demand for optical signal processing. In the past decade, all-optical signal processing techniques have attracted the attention of many researchers. High-speed all-optical logic gates play a vital role in all-optical signal processing systems and networks. Many techniques have been implemented so far to realize all-optical logic gates such as semiconductor optical amplifiers (SOAs) [2–4], semiconductor ring resonators [5,6], periodically poled lithium niobate (PPLN) waveguides [7–9], and photonic crystals [10–12].

The response time of the SOA and microresonator-based logic gates depends mostly upon the carrier's recovery time which leads to decrease in the operational speed of these all-optical logic gates. Furthermore, these logic gates are affected by inevitable spontaneous noise [13,14]. These logic gates have been improved using Mach–Zehnder interferometer-based designs. Still, they are limited by the complex integration and high sensitivity to the random phase changes [15]. The logic gates based on semiconductor ring resonators are simple and consume low input signal power but they are limited by high dimensions and relatively low speed [16–18]. PPLN waveguide-based logic gates have bagged the advantages of fast response, bit rate and data format independency, insignificant spontaneous emission noise, and complete transparency. In spite of these advantages, they are restricted by minimum size, polarization, and temperature dependency [7–9,13,14,19–21].

The unique properties of photonic crystal, such as high speed, compactness, low power consumption, and better confinement, allowed the designers to construct the optical devices. A lot of work has been done in realizing the logic gates using photonic crystals in which multi-mode interference (MMI) [22,23], photonic crystal ring resonators [24–26], Y-shaped waveguides [27], self-collimation [28,29] are among the few. But these techniques are lagging in providing high bit rate in order to fruitfully use the logic gates for high-speed telecommunication applications. The photonic crystal-based AND gates that have been reported so far provide a bit rate less than 0.83 Tbps. To improve the bit rate, we designed the AND gate structures using T-shaped waveguide. To the best of our knowledge, a T-shaped waveguide has not ever been used in designing all-optical logic gates.

In this paper, we proposed two different photonic crystal-based AND gate structures using a T-shaped

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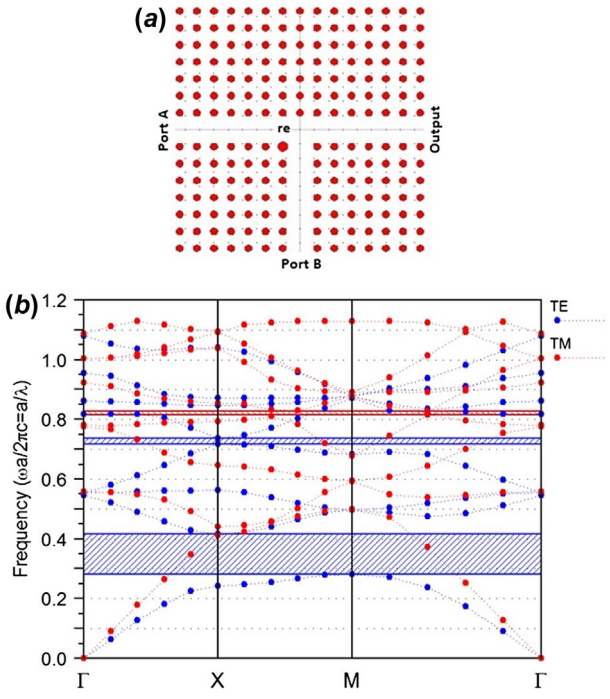

Figure 1. Proposed all-optical AND gate without probe input (*a*) structure and (*b*) band diagram. (The colour version of this figure is included in the online version of the journal.)

waveguide. The first AND gate structure is designed with a single T-shaped waveguide and a bit rate of 6.26 Tbps is achieved. The second AND gate structure is designed using two T-shaped waveguides which needs a probe input signal for its operation. This is basically designed to improve the contrast ratio, and the achieved value of the contrast ratio is 9.66 dB with a bit rate of 3.58 Tbps. The comparison of the proposed structures with other AND gate structures found in the literature shows that our proposed AND gate structures have higher bit rate and contrast ratio.

This paper is organized as follows. The operating principle and the optimization procedure of AND gate with single T-shaped waveguide are explained in Section 2. Section 3 presents the simulation results and the analysis. The operating principle and the optimization procedure of the AND gate with probe input are explained in Section 4 which is followed by its simulation results and analysis in Section 5.

2. Design of AND gate using T-shaped waveguide without probe input

2.1. Model and operating principle

A new photonic crystal structure with T-shaped waveguide is designed using a two-dimensional 15 × 15 array of Si rods with air background. It is a structure of square-type lattice with cylindrical Si rods, whose refractive index is set to 3.46. The radius of these rods is 0.2*a*, where *a* is a lattice constant of value 0.6 μm. This structure can operate as an AND gate with proper output power levels against the input combinations. This structure is illustrated in Figure 1(*a*) with input ports A and B and output port Z. By optimizing the radius of the T-junction edge rod r_e, we can achieve better output power levels for the respective input combinations. The forbidden wavelength range of light or photonic bandgap can be obtained from the band diagram and it is calculated using PWE method. According to the band diagram, there are three photonic bandgaps out of which two are for TE mode and one is for TM mode as shown in Figure 1(*b*). A photonic bandgap suitable for the telecommunication window has a range of 0.282568 (a/λ)–0.416924(a/λ). Thus, it completely reflects the light signal of wavelength ranging from 1.44 μm to 2.12 μm.

The rod r_e in the structure is optimized such that a low power level at single input combinations is achieved and its optimized value is 0.28*a*. Apart from this, the size of the proposed AND gate is 8.64 μm × 8.64 μm which may be the smallest photonic crystal all-optical AND gate that has ever been proposed in the literature as per the best of our knowledge. Moreover, the functional behavior of this structure depends upon the interference phenomenon.

The interference of the light beams depends upon wave optics theory. According to the wave optics theory, the constructive interference occurs when the phase difference and the path difference are $2n\pi$ and $n\lambda$, respectively (where λ is free space wavelength of the light and $n = 0, 1, 2, 3, \ldots$). The destructive interference occurs when the phase difference and the path difference are $(2n + 1)\pi$ and $(2n + 1)\lambda/2$, respectively. With a zero phase difference and a zero path difference between the applied input light beams at the ports A and B, a constructive interference occurs for which the output power level is considered to be logic-1. The optimized radius of the rod r_e will keep this output power value near to the input power P_a. For the single input at port A or port B, the rod r_e acts as a cavity and absorbs some light power. The resultant power at the output port Z will be less such that it can be considered as logic-0. The proposed AND gate without probe input works better at the wavelength of 1.55 μm with high contrast ratio as illustrated in Figure 2. The minimum value of ON to OFF contrast ratio has been calculated from the simulated values to determine the performance of the structure at the different wavelengths in the photonic bandgap. The minimum value of the contrast ratio of the AND gate can be obtained with the output power level of logic-1 and the maximum value of the logic-0 power level. The minimum value of the contrast ratio obtained for the proposed AND gate is 5.74 dB. So, the Figure 2 clearly shows that the proposed AND gate works better in telecommunication wavelength range.

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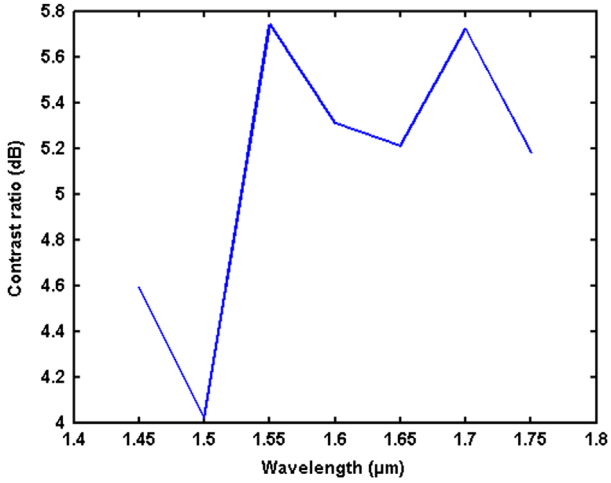

Figure 2. Normalized operating wavelength vs. contrast ratio. (The colour version of this figure is included in the online version of the journal.)

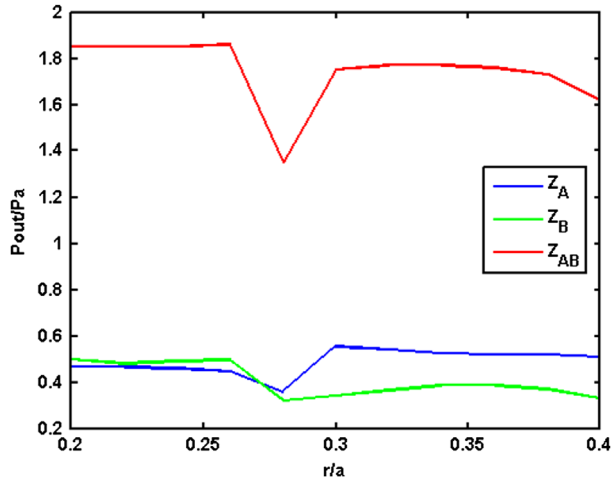

Figure 3. Plot of *r*/*a* vs. power ratio. (The colour version of this figure is included in the online version of the journal.)

A low power level of logic-0 will provide a high contrast ratio as compared to the larger value of the power level of logic-1. The ON to OFF logic level contrast ratio CR is given by

$$\mathrm{CR} = 10\,log\,\frac{P_1}{P_0} \tag{1}$$

where P_1 is the power level of logic-1 and P_0 is the power level of logic-0. A large deviation in the output power values of logic-1 and logic-0 will provide a high contrast ratio. A very low value of logic-0 will contribute more to attain a high contrast ratio.

2.2. Optimization of the rod 'r_e'

The radius of the rod r_e is optimized such that a low output power level can be obtained for the input combinations '01' and '10' in order to get a high contrast ratio. We have changed the radius of the rod r_e from 0.2*a* to 0.4*a*. A low output power level is obtained at a radius of 0.28*a* for single input combinations and also for both the inputs applied. An output power obtained at a radius of 0.28*a* for the two input combinations '01' and '10' is less than 0.37 P_a. The output power for the input combination '11' is also near to the applied input power P_a (not more than 1.35 P_a) which has been taken as a reference.

The output performance of the AND gate structure at various radius values of rod r_e is shown in Figure 3. Z_A indicates the power level at the output port Z when a single input is applied at port A and Z_B indicates the power level at the output port Z when a single input is applied at port B. Similarly, Z_{AB} is the power level at the output port Z when the light beam is applied to both the input ports A and B. A low output power is available at the wavelength of 1.55 μm for single input combinations (i.e. individual inputs at port A and port B) and an output power level of more than P_a is obtained for both inputs applied. Other than the radius of 0.28*a*, the output power is more than 0.45 P_a for the single input at port A and is more than 0.35 P_a for the single input at port B.

3. Results and discussion for AND gate without probe input

The normalized operating wavelength of the proposed structure is obtained using the PWE method. Simulation has been done on the structure with optimized rod dimensions of $r = 0.2a$ and $r_e = 0.28a$ using the FDTD method. To absorb the waves and avoid the reflection at the boundaries, simulation has been done by employing perfectly matched boundary conditions. The electromagnetic waves propagating in the (x, z) plane and the magnetic field polarization has been chosen in such a way that it is parallel to the axis of the Si rods i.e. *y*-axis. The FDTD method must solve Maxwell's equations by discretizing the fields into space and time. Space grids are chosen such that $\Delta x < \lambda/10$ and $\Delta z < \lambda/10$, to guarantee convergence in the simulation, where *x*- and *z*-axes are the horizontal and vertical direction coordinates, respectively. To obtain stable simulations, the space grid and the time grid are chosen in order to satisfy the following Courant condition [30]:

$$c\Delta t < \frac{1}{\sqrt{(\Delta x)^2 + (\Delta z)^2}} \tag{2}$$

where *c* is the speed of light in free space.

The simulation results are shown in Figure 4 wherein, the optical field patterns for the three input combinations

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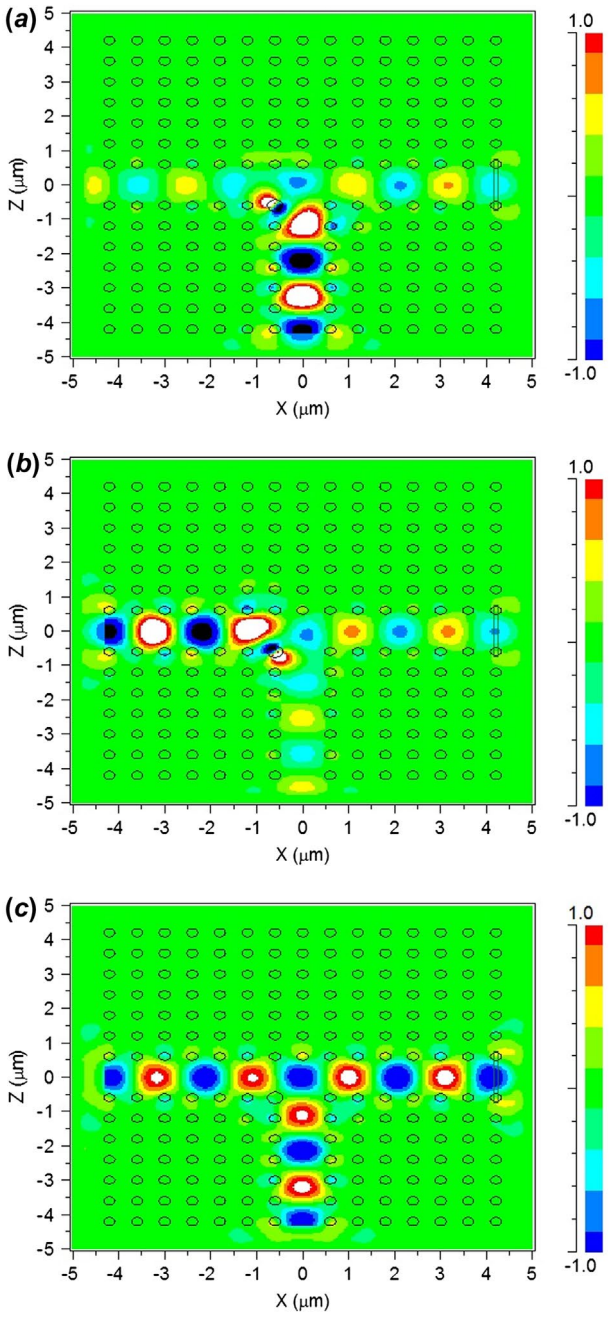

Figure 4. Optical field pattern of AND gate without probe input for the input combinations (*a*) 01 (*b*) 10, and (*c*) 11. (The colour version of this figure is included in the online version of the journal.)

'01,' '10,' and '11' can be observed. For an input light beam at port A and no light at port B, an output power of 0.36 P_a is obtained. This value is considered to be logic-0. Similarly, for an input light beam at port B and no light at port A, an output of 0.32 P_a is obtained. This value is also considered to be logic-0.

When both the input ports are applied with light beam, the output power obtained is 1.35 P_a and it is considered to be logic-1. In all the three cases, the rod r_e acts as a cavity which will absorb some optical power so that the total amount of the power cannot reach the output. At the

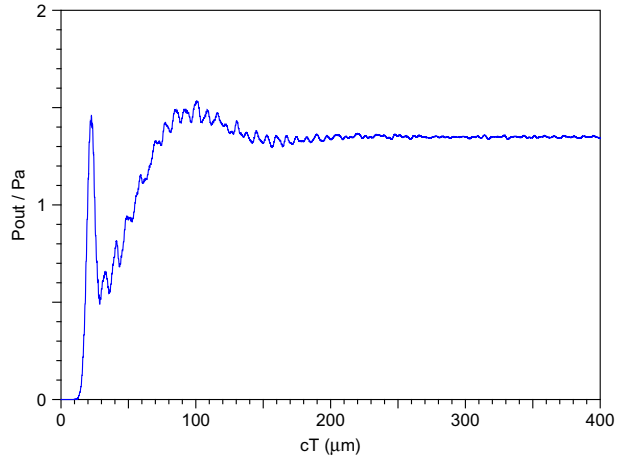

Figure 5. Time evolving curve of the output power of AND gate without probe input. (The colour version of this figure is included in the online version of the journal.)

normal radius of the rod r_e, the output power will be nearly half of the applied input for the single input condition. For both the inputs applied, the output power is nearly double the applied input power.

The response period of the proposed AND gate can be calculated using the time evolving curve of the output power same as in [30,27]. The time evolving curve of the output curve is given in Figure 5. We can observe from the Figure 6 that the time required to move from 0 to 90% of the average output power P_{avg} is t = 0.0734 ps (or ct = 22 μm). The time t consists of two components, t_1 and t_2, where t_1 is the time due to transmission delay and t_2 is the time required to move from 0.1 to 90% of the average output power P_{avg}. The time components that can be observed are t_1 = 0.0335 ps and t_2 = 0.0399 ps. As the entire system operates on the linear materials, it can be expected that the falling time required to reach from P_{avg} to 10% of P_{avg} is approximately equal to t_2. So, a narrow pulse of width $2t_2$ = 0.0798 ps can be produced at the output. Suppose, the ON time is equal to OFF time, the response period of the output signal from the AND gate is 0.1596 ps. So, the proposed gate can operate at a bit rate of 6.26 Tbps. The response period of the proposed AND gate without probe input is far better than the triangular lattice-based Y-shaped AND gate [27].

As a comparison with the proposed AND gate, we designed and simulated a Y-shaped AND gate with same dimensional parameters as reported in [27]. We assumed the lattice constant value as 0.472 μm in order to set the photonic bandgap in the telecommunication window. The structure of the Y-shaped AND gate and its time evolving curve is shown in Figure 6. The output power for each input combination is given in Table 1 for both the Y-shaped AND gate and the proposed T-shaped AND gate. The response period of this AND gate structure is calculated same as in [27]. The response period obtained

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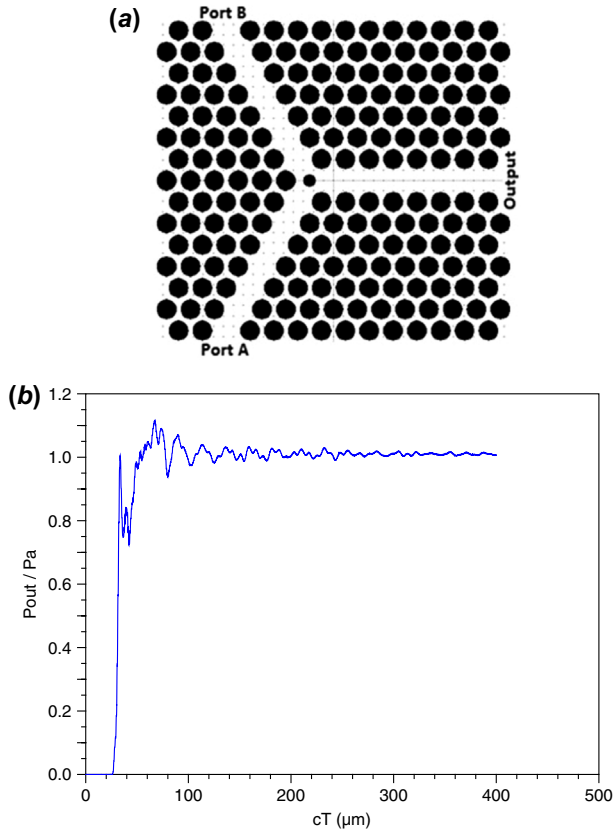

Figure 6. Y-shaped AND gate (*a*) structure and (*b*) time evolving curve. (The colour version of this figure is included in the online version of the journal.)

Table 1. Truth table and the output power levels of both T-shaped and Y-shaped AND gates.

Input A	Input B	Output logic	Output Z (mW) (T-shaped AND)	Output Z (mW) (Y-shaped AND)
0	0	0	0	0
0	1	0	0.32 P_a	0.252 P_a
1	0	0	0.36 P_a	0.252 P_a
1	1	1	1.13 P_a	1.05 P_a

from the time evolving curve is 1.172 ps i.e. the Y-shaped AND gate works at a bit rate of 0.853 Tbps. Hence, the bit rate of T-shaped AND gate is far better than Y-shaped AND gate. This is mainly because of the type of the lattice used and the type of the background. In Y-shaped AND gate, the structure consists of holes in the Si substrate; whereas in the T-shaped AND gate, the structure has Si rods in the air background. Also, the proposed T-shaped AND gate is better than the ring resonator-based AND gate of triangular lattice-type structure [25] in terms of the bit rate. But the contrast ratio of the Y-shaped AND gate is larger than the T-shaped AND gate.

The minimum ON to OFF logic level contrast ratio of the proposed AND gate can be obtained from the output of the input combinations '10' and '11' and the value is 5.74 dB. As the AND consists of only one input combination for which output is logic-1, we used that value for the calculation of both minimum and maximum values of the contrast ratio. The maximum value of the contrast ratio can be obtained with the minimum acquired output power level of logic-0. In this case, we use the power of the input combination '01' and the value is 6.68 dB. Though its contrast ratio is small compared to the available AND gates in the literature, its bit rate is very high. In order to improve the contrast ratio, we proposed another AND gate with probe input.

To the best of our knowledge, this is the smallest AND gate that has ever been reported in the literature. Furthermore, the simulation results show that the proposed T-shaped AND gate without probe input can be as small as $8a \times 8a$ without disturbing the output power levels. The unwanted reflection into the unemployed input ports is to be reduced in this AND gate to improve the functional performance.

4. Design of AND gate using double T-shaped waveguides with probe input

4.1. Model and Operating principle

We proposed another photonic crystal AND gate using two T-shaped waveguides in series as shown in Figure 7. The size of the T-shaped waveguide in this AND gate structure is $8a \times 8a$. The entire AND gate structure with probe input consists of 9×14 array of cylindrical rods of Si material with air background arranged in the form of square-type lattice. The lattice constant and the refractive index of the Si material are same as in the proposed AND gate without the probe input. As the T-shaped waveguides are in series, one horizontal and two vertical waveguides are observed among which vertical waveguides are utilized to apply the inputs A and B. The left side of the horizontal waveguide is applied with a probe signal and the right side of the horizontal waveguide is used to obtain the output signal. The normalized operating wavelength is calculated using PWE method whose range is same as that of the previous structure with a very little change in that value. The forbidden wavelength range of light is from $0.282568(a/\lambda)$ to $0.416924(a/\lambda)$ to which the photonic crystal structure cannot allow them to pass through it. The proposed AND gate with probe input is basically designed to improve the contrast ratio.

The radius of the rod r_e at both the junctions is optimized to $0.3a$ in order to get high contrast ratio as well as low unwanted reflection into the unemployed input ports. The size of this structure is also very small with a dimension of 8.64 μm × 5.64 μm.

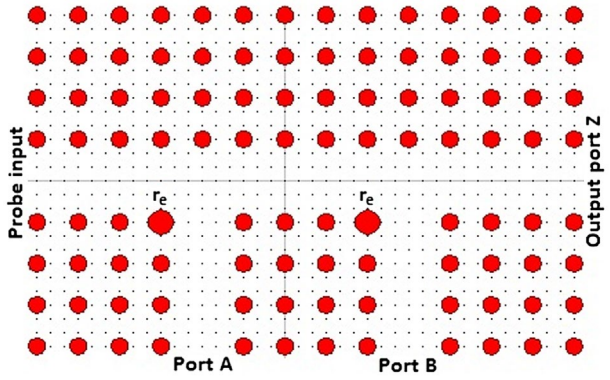

Figure 7. Proposed structure of AND gate with probe input. (The colour version of this figure is included in the online version of the journal.)

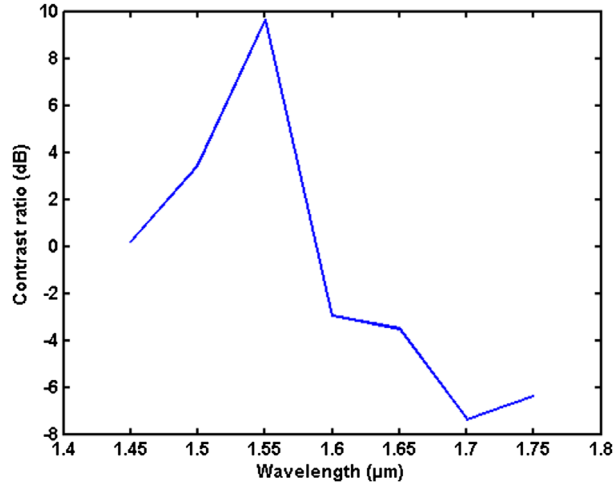

Figure 8. Normalized operating wavelength vs. contrast ratio. (The colour version of this figure is included in the online version of the journal.)

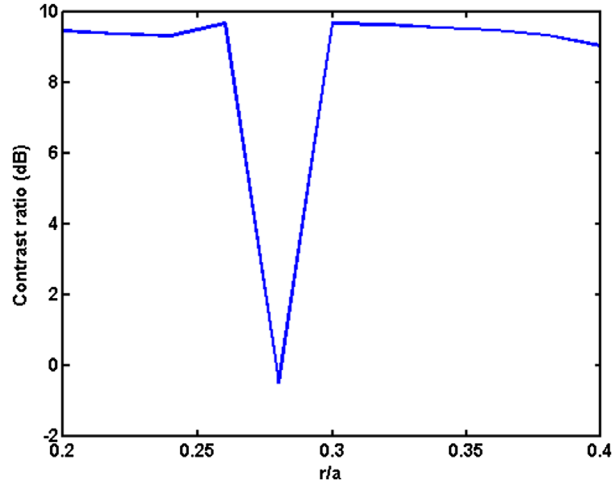

Figure 9. Plot of *r*/*a* vs. contrast ratio. (The colour version of this figure is included in the online version of the journal.)

In the interference-based designs, sometimes there is a need to use a probe input so as to provide a proper output for the required input combination. For example, in the logic gates like AND, XNOR, and NOR, the output is to be logic-0 for single input (i.e. when the input combination is '01' and '10'). In such a condition, the applied input light beam is to be canceled out in order to obtain a very low or negligible light power at the output port. This cancelation of input power occurs due to the destructive interference which leads to a very low output power, considered as logic-0. This low value of logic-0 output power will provide a high contrast ratio. Similarly, this probe input will act as an output power when inputs are not applied (i.e. when the input combination is '00') to the logic gates like NOT, NOR, NAND, and XNOR. This output power will be such that it can be considered as logic-1.

At the first T-junction of the structure, the two light beams from the probe input port and the input port A has no path difference and reach the junction at a time. This will lead to have constructive interference at a phase difference of 0° and the destructive interference at a phase difference of 180°. At the second T-junction, the path difference between the input light beam from the port B and the probe input is 5*a*. This path difference will not allow these two light beams to reach the junction simultaneously, and it will make them to be destructively interfering with each other at a phase difference of 0°. The constructive interference can be obtained at the second T-junction with 180° phase difference. According to this interference pattern, the phase of the input light beams is determined to get the proper output.

The proposed AND gate structure provides a good performance at a normalized wavelength of 1.55 μm which comes in optical communication window. At this wavelength, the contrast ratio is high as illustrated in Figure 8. The unwanted reflection into the unemployed input ports is also very less at this wavelength. In this structure with probe input, the basic need is to change the phase of logic-1 input at the respective port. Due to the proper phase values at the respective ports, a required output logic can be obtained.

4.2. Optimization of the rod 'r_e' for high contrast ratio

We optimized the rod r_e at both the T-junctions of the structure in order to get high contrast ratio and low unwanted reflection into the unemployed inputs. We changed the radius of the rod r_e at both the T-junctions and observed the output for all the input combinations. The minimum value of the contrast ratio has been calculated at each value of the rod radius. The overall performance of this structure at each value of r_e is illustrated in

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Figure 9. The radius of rod r_e at which a high contrast ratio achieved is 0.3a. This optimized radius of rod r_e is also very helpful in decreasing the reflection into the unemployed input ports. The amount of the unwanted reflection into the unemployed inputs is less than 0.1 P_a. The normal size of the rod r_e will produce high unwanted reflection more than 0.3 P_a. This value is more than the power level of logic-0 at the output. So, the optimized radius of the rod r_e gives a good performance with respect to the output power levels and the unwanted reflection.

At the optimized radius of r_e, the contrast ratio achieved is 9.66 dB. We optimized the radius of r_e by observing the minimum value of the ON to OFF logic level contrast ratio. Usually, minimum value of the contrast ratio is used to define the performance of the structure.

5. Results and discussion for AND gate with probe input

The simulation method used for the previous structure has been implemented to simulate this structure also. This AND gate structure should also be simulated for the input combination '00' as it was not the case in the previous AND gate structure without the probe input. This is due to the probe input which is always applied at its port for all the input combinations. For the input combination '00,' though the input light beam is not applied to both the ports A and B, the probe input applied will reach the output port Z and contributes less power due to the rod r_e that leads to logic-0. The optical field patterns for all the possible input combinations are shown in Figure 10.

The phase of the probe input is kept at 180° for all the input combinations. The phase of the input light beam applied at the input ports is to be changed in accordance with the required output logic. For the input combination '00,' the probe signal is the only source of light and a power of 0.24 P_a reaches the output due to the optimized rod r_e at both the T-junctions. This is considered to be logic-0. For the input combination '01,' the phase of the input light signal at port B is 180° so that it can be destructively interfered with the probe signal and provides a low power at the output. Similarly, for the input

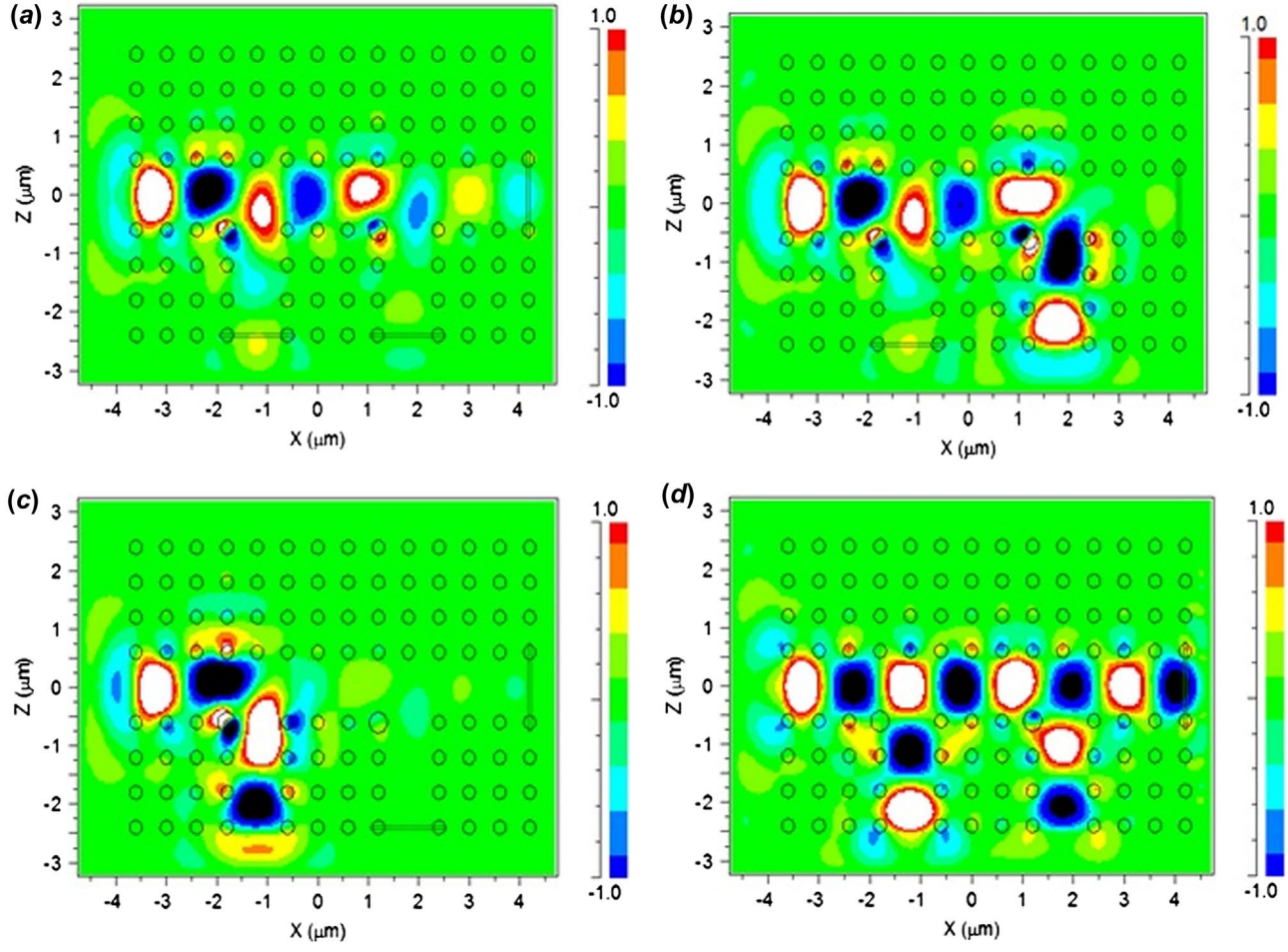

Figure 10. Optical power level of AND gate with probe input for the input combinations (*a*) 00 (*b*) 01 (*c*) 10, and (*d*) 11. (The colour version of this figure is included in the online version of the journal.)

Table 2. Summary on the type of interference occurred with phase difference between the input light beam and the probe input at each T-junction.

Input combinations		At the first T-junction		At the second T-junction	
A	B	Phase difference	Type of the interference	Phase difference	Type of the interference
0	0	–	–	–	–
0	1	–	–	180°	Destructive
1	0	0°	Destructive	–	–
1	1	180°	Constructive	0°	Constructive

Table 3. Output power levels of AND gate with probe input.

Input A	Input B	Output Z	
Logic value	Logic value	P_{out} (mW)	Logic value
0	0	0.240 P_a	0
0	1	0.025 P_a	0
1	0	0.011 P_a	0
1	1	2.220 P_a	1

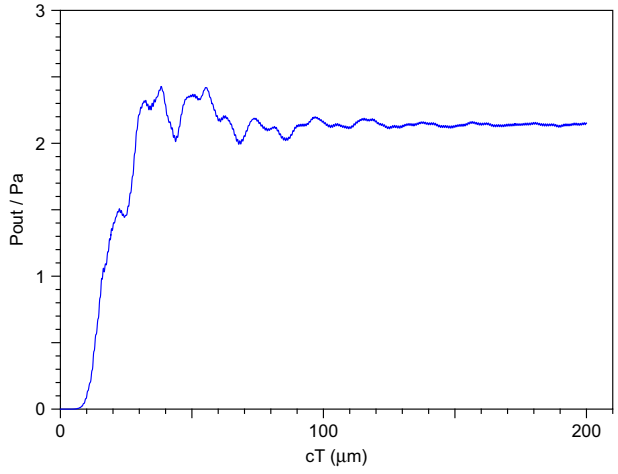

Figure 11. Time evolving curve of the output power of the AND gate with probe input. (The colour version of this figure is included in the online version of the journal.)

combination '10,' the phase of the input light beam at port A is 0° such that it can be destructively interfered with the probe signal and provides a low power at the output. Finally for both the inputs applied at the ports A and B, the phases of the input signals at ports A and B are 180° and 0°, respectively. At both the T-junctions, the constructive interference occurs and the amount of power that reaches to the output port Z is larger than the reference input P_a. Table 2 summarizes the phase difference between the input light beam and the probe input beam along with the type of the interference occurred at each T-junction for each input combination. In order to change the phase of the inputs, external phase shifters are required. However, in our work, the phase change of the inputs is taken care in the simulation. The summary on the output power corresponding to the input combinations along with their logic values is given in Table 3.

The response period of the proposed AND gate is calculated using the time evolving curve same as the previous case as it is in [30,27], which is shown in Figure 11. It can be observed from the time evolving curve that the time required to move from 0 to 90% of the average output power.

P_{avg} is t = 0.0937 ps (or ct = 28.1 μm). The time due to the transmission delay t_1 is 0.024 ps and the time to move from 0.1 to 90% of the average output power t_2 is 0.0697 ps. As the fall time is considered to be approximately equal to the rise time due to the linear materials, a narrow pulse width $2t_2$ = 0.1394 ps can be produced at the output. So, the response period of the output signal from this proposed AND gate is 0.2788 ps and can operate with a bit rate of 3.58 Tbps.

The bit rate of the proposed AND gate with probe input is far better than the triangular lattice-based AND gate structure with Y-shaped waveguide [27] and the triangular lattice-based AND gate structure with ring resonators and Y-shaped waveguide [25]. As the bit rate of this structure is in Tbps, it can be fruitfully utilized for the high-speed telecommunication systems and networks.

The minimum value of ON to OFF contrast ratio of the proposed AND gate with probe input can be obtained from the output power levels of the input combinations '00' and '11' and its value is 9.66 dB. The maximum value of the contrast ratio can be obtained from the output power levels of the input combinations '01' and '11' and the value is 19.46 dB. We used the minimum value of the contrast ratio to compare with the AND gate structures available in the literature. In terms of the contrast ratio, the proposed AND gate is better than the MMI-based AND gate [22], Y-shaped waveguide-based AND gate [27,31], and ring resonator-based AND gate [32,25]. The contrast ratio of all these AND gates is not more than 7 dB.

6. Conclusion

In this paper, a new configuration to design a photonic crystal-based all-optical AND gate has been proposed using T-shaped waveguide in two-dimensional square lattice of Si rods in air. The device performance is analyzed and simulated by PWE and FDTD methods. The method of operating a single T-shaped waveguide as an AND gate

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without probe input and the performance of a double T-shaped waveguide as an AND gate with probe input has been explained. The significance of the probe input in improving the functional performance of the AND gate and the method of optimizing parameter for determining the high contrast ratio are explored. The AND logic gate without the probe input provides a bit rate of 6.26 Tbps with a minimum contrast ratio of 5.74 dB. The AND gate with probe input provides a bit rate of 3.58 Tbps with a minimum contrast ratio of 9.66 dB. The size of these gates is as small as they can be applied for the chip-level integration. It is expected that the new proposed designs will help in realizing devices and components for high-speed broadband optical communication systems and networks.

Disclosure statement

No potential conflict of interest was reported by the authors.

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